UNIVERSITY of VIRGINIA

ENVIRONMENTAL RESILIENCE INSTITUTE

# Leading the Way on Climate Restoration: Environmental and Economic Opportunities for Virginia

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# Report Background

This report provides a preliminary estimate of the amount of $CO_2$ that Virginia can remove annually from the atmosphere and store long term within its borders.




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The Environmental Resilience Institute supports transdisciplinary research and training at the intersection of environmental change and human well-being by connecting faculty, students, and citizens together to foster a more resilient and sustainable future for the global common good.

In early 2020, ERI researchers began to explore how to implement negative emissions strategies (removal of carbon dioxide from the environment) throughout Virginia, to understand the interplay between negative emissions, communities, and existing economic and social activities—and analyze potential barriers and ancillary benefits of carbon mitigation. Future research will explore how to accelerate the deployment of negative emissions strategies, how to create incentives for their adoption, and how to assess the costs of doing nothing.

The goal of the Climate Restoration Initiative is to produce recommendations on pathways to negative emissions in Virginia and create mapping tools to inform state and community decision-making. This work will position Virginia as a model state in developing integrated negative emissions strategies that can be translated throughout the nation.

# 1 /Introduction

Climate change is an increasingly urgent problem for Virginia and the global society.  Mitigating it will require a rapid curtailment of greenhouse gas pollution, primarily emissions of carbon dioxide ($CO_2$). The Virginia legislature recently established two ambitious climate change mitigation goals. The Virginia Clean Economy Act requires that all electricity generated in the state be from carbon-free sources by 2050. A separate statute requires the preparation of a Virginia Energy Plan that identifies pathways to a net-zero energy economy in the state by 2045.

Effective climate mitigation and achieving a net-zero energy economy will also require carbon removal in order to offset emissions from transportation, industry, and other activities that produce carbon emissions that are expensive or technologically difficult to cut. This report provides a preliminary estimate of the amount of $CO_2$ that Virginia can remove annually from the atmosphere and store long term within its borders. The level of $CO_2$ removal that Virginia needs to achieve a net-zero emissions goal will depend on how that goal is defined and the progress the state can make in cutting emissions in key sectors of the economy. Although some incremental $CO_2$ removal can be realized through nature-based approaches (such as restoring forests), there are biophysical limits on how much we can sequester through these processes. If cuts to emissions continue as slowly as they have for the past decade, the state will need more intensive forms of $CO_2$ removal such as bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) in order to achieve net-zero goals.

Our analysis suggests that Virginia can achieve net-zero energy-related greenhouse gas emissions by decarbonizing the electric power sector, transitioning to electric vehicles and carbon-neutral transportation fuels, expanding electrification of the building sector, and deploying BECCS and potentially DAC to offset any remaining emissions. Figure 1 presents summary results from our integrated modeling that show expected decarbonization progress and the need to implement large scale $CO_2$ removal by 2050. All of these forms of $CO_2$ removal will present unique environmental and economic tradeoffs and opportunities, which are discussed in this report.

A recent study conducted by the University of Virginia's Energy Transition Initiative identified pathways to decarbonize Virginia's energy system with only a small increase in energy expenditures as a percentage of overall economic activity (Shobe et al., 2021). Given the magnitude of Virginia's existing natural carbon sinks and the potential for increasing negative emissions within the state, the Commonwealth has an opportunity to look beyond net-zero CO2 emissions and seek to achieve net-negative emissions for all greenhouse gases by 2050. That goal could be realized by approaching net-zero energy related CO2 emissions while also implementing measures to safeguard and expand natural carbon sinks within the state.

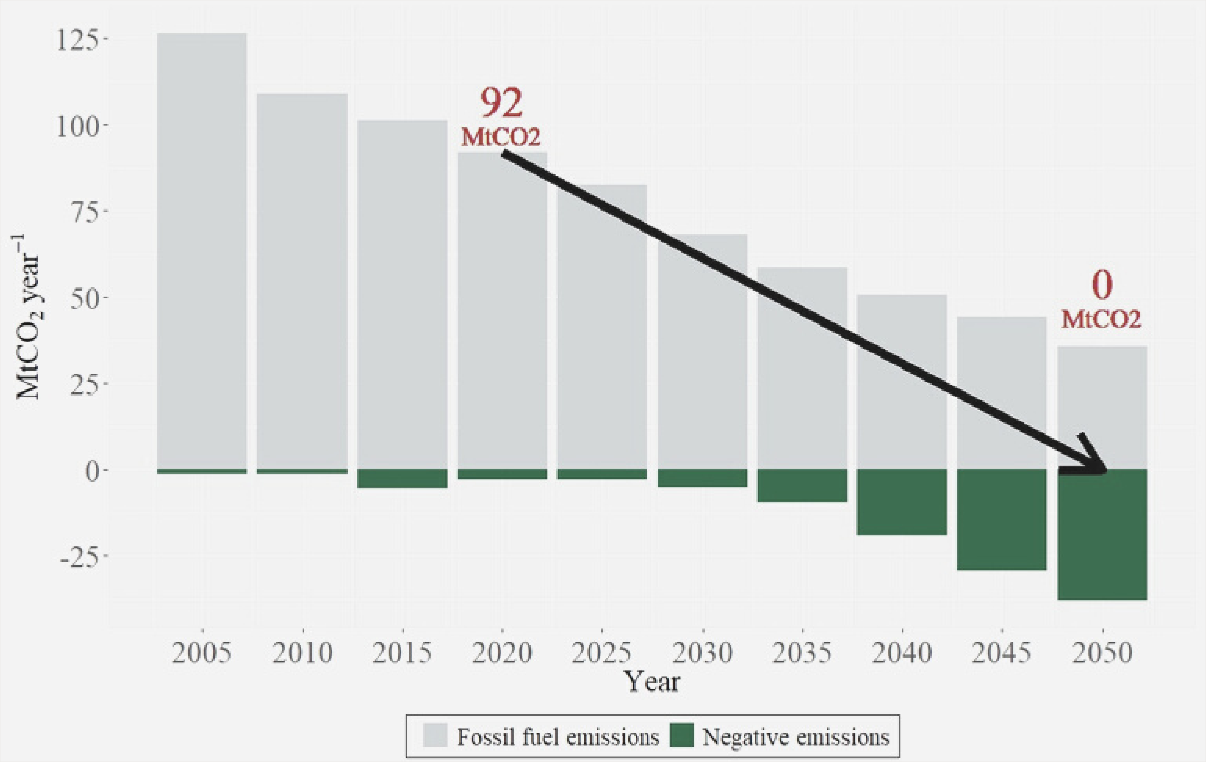


**Figure 1.** Model projections of state-level greenhouse gas emissions in Virginia under a scenario in which emissions reach net-zero by mid-century (excluding potential new policy on transportation).

In the model projections in Figure 1, steady reductions in CO2 emissions are anticipated, and residual emissions in transportation, industry, and buildings (shown collectively as gray bars here) will need to be offset by CO2 removal activities (shown in green) in order to meet Virginia's net-zero goals. We estimated the potential for additional capture and sequestration of CO2 in Virginia by restoring both natural ecosystems and the health of agricultural soils.

To arrive at this estimate, we used several modeling tools to evaluate:

- The lands in Virginia with highest potential for reforestation and the amount of carbon per year that could be sequestered on those lands through reforestation through 2050.
- The carbon mitigation potential of changing agricultural practices in Virginia and the amount of carbon per year that could be sequestered on agricultural lands in Virginia through 2050.
- Coastal areas in Virginia with potential for wetland and seagrass restoration (incorporating the effects of sea-level rise) and the amount of $CO_2$ per year that could be sequestered in the state through those practices through 2050.

We conclude that natural strategies – reforestation, improved soil health, and coastal ecosystem restoration – can sequester or otherwise mitigate an average of 8.6 million tons of $CO_2$ per year in 2050, in addition to the 51.8 million tons a year these lands are currently sequestering [REM1] (Virginia Department of Environmental Quality). This is an estimate with numerous assumptions built in, but it does accurately represent the order of magnitude of carbon that Virginia might be able to sequester through natural processes. This estimate should be considered a maximum for decision-making purposes. The state is unlikely to achieve this level of natural $CO_2$ removal, primarily because sequestering carbon through natural processes requires large amounts of land, and landowners in Virginia are unlikely to shift all possible acreage for $CO_2$ removal by 2050.

Our analysis also shows that Virginia may need as much as 40 million additional tons per year of $CO_2$ removal by 2050 to achieve net-zero energy related emissions in a cost-effective fashion, depending on how quickly and how much we decarbonize energy use and transportation. We estimate that natural strategies can only be reasonably expected to contribute up to 20 percent of that. Virginia does, however, have the potential to achieve significant and cost-effective $CO_2$ removal through BECCS. This technology converts biofuels, such as switchgrass or wood, into energy and sequesters the $CO_2$ that results from the process in geologic formations. Assuming an aggressive program to reduce $CO_2$ emissions and implementation of natural strategies, Virginia should be able to use BECCS to provide the majority of carbon removal needed to achieve net-zero by 2050.

# 2 /Virginia Carbon Emissions and Mitigation Policies

Until recently Virginia had virtually no climate change mitigation policies. With the passage of the Virginia Clean Economy Act and other legislation, Virginia has now moved to the forefront of states seeking to reduce greenhouse gas emissions from electricity generation and transportation. Nevertheless, substantial work remains to achieve net-zero emissions across the state's entire economy.

## Virginia Greenhouse Gas Emissions and Existing Sequestration

In 2018, the Virginia Department of Environmental Quality estimated that energy use and other economic activities within the state generate 141.8 million tons of carbon dioxide ($CO_2$)-equivalent greenhouse gas emissions each year. Considering the 51.8 million tons of $CO_2$-equivalent sequestered by forests and other land uses, the net greenhouse gas emissions are currently 90.1 million tons of $CO_2$-equivalent per year.

Table 1 lists the sources and sinks of $CO_2$-equivalent per year in Virginia. $CO_2$-equivalent is a measure used to compare the various greenhouse gases based on their global warming potential.

| | $CO_2$ | $CH_4$ | $N_2O$ | Other | **Total** |
|---|---|---|---|---|---|
| | (in MMTCO2e) | | | | |
| **Source/Sector** | | | | | |
| Transportation | 48.5 | 0.1 | 0.4 | 0 | **48.9** |
| Industry | 20.5 | 0.1 | 0.1 | 4.6 | **25.2** |
| Commercial | 24.7 | 0 | 0 | 0 | **24.7** |
| Residential | 23.5 | 0.1 | 0 | 0 | **23.7** |
| Energy Production, Transport & Distribution | 0 | 6.9 | 0 | 0 | **6.9** |
| Agriculture | 0.2 | 3.1 | 3.2 | 0 | **6.4** |
| Landfills | 0 | 4 | 0 | 0 | **4** |
| Waste Incineration | 1 | 0 | 0 | 0 | **1** |
| Wastewater | 0 | 0.7 | 0.3 | 0 | **1** |
| Total Emissions | 118.4 | 14.9 | 4 | 4.6 | **141.8** |
| Flux from Forestry & Other Land Uses | -51.8 | 0 | 0 | 0 | **-51.8** |
| **Total Net Emissions** | **66.6** | **14.9** | **4** | **4.6** | **90.1** |

**Table 1.** Sources and Sinks of Greenhouse Gas Emissions in Virginia (units are million metric tons of CO2-equivalent per year)

Based on this estimate, the state could achieve a goal of net-zero CO2 emissions by reducing energy-related CO2 emissions by 56% if the state's nature-based carbon sink continues to sequester CO2 at its current rate. A somewhat more ambitious net-zero goal that encompasses all greenhouse gas emissions could be achieved by reducing total greenhouse gas emissions by 64% on a CO2-equivalent basis, while maintaining existing nature-based carbon sinks. This report, together with CO2 emissions reduction modeling completed by University of Virginia's Energy Transition Initiative (Shobe et al., 2021), indicates that it is feasible from both an economic and technological perspective for Virginia to achieve net-zero energy-related CO2 emissions by sharply reducing emissions attributable to energy use while also incorporating engineered negative emissions technologies such as bioenergy with carbon capture and storage (BECCS) into the state's energy system. If the state also maintains and enhances existing natural carbon sinks, the state could achieve net-negative greenhouse gas emissions [**1**].

[**1**] This report follows international guidelines for distinguishing between natural and anthropogenic sources of emissions from agriculture, forestry, and land use. The Intergovernmental Panel on Climate Change (IPCC) has provided guidance that sources and sinks of emissions from managed land should be considered anthropogenic sources and included in national greenhouse gas inventories and emission reduction commitments (Ogle et al., 2021). The reporting guidelines define managed land as "... land where human interventions and practices have been applied to perform production, ecological or social functions" including conservation, recreation, and cultural uses and objectives (IPCC 2003). In U.S. national greenhouse gas inventories and CO2 emissions reduction commitments, the entire land area of the contiguous 48 states, including all of Virginia, is classified as managed land (USEPA 2021).

## Virginia Greenhouse Gas Mitigation Policies

In the 2020–21 session, the Virginia legislature passed three bills that together established the state's climate change mitigation framework. The Virginia Clean Economy Act requires that all electricity generated in the state be carbon-free by 2050. It also sets specific targets for offshore wind and solar generation in the state. Finally, the statute requires the state to prepare an energy plan that identifies actions that would achieve net-zero emissions by 2050 from all sectors of Virginia's economy. The legislature also passed the Clean Energy and Community Flood Preparedness Act, which authorized Virginia to join the Regional Greenhouse Gas Initiative, a greenhouse gas emissions offset program that currently includes ten other eastern states, with two more (Pennsylvania and North Carolina) in the process of joining. The Regional Greenhouse Gas Initiative allows regulated greenhouse gas emitters in member states to purchase offsets for a portion of their emissions, including offsets in the form of projects that remove and sequester $CO_2$ from the atmosphere. Finally, SB1374 established a task force to study carbon sequestration in the state and report back to the legislature.

The legislature passed these Virginia-centric policies against a backdrop of extensive efforts nationally and globally to both cut and offset greenhouse gas emissions. Twenty-four states have set some kind of $CO_2$ emissions targets. The University of Virginia, Virginia Tech, and William and Mary have all adopted goals of achieving carbon-neutral campuses by 2030. Many large corporations, some with significant presence in Virginia, have adopted net-zero or net-negative $CO_2$ emissions goals. For example, Amazon has pledged to be net carbon-neutral by 2040 and Microsoft has pledged to be carbon-negative by 2030 and to remove all its historic $CO_2$ emissions from the atmosphere by 2050 (Amazon 2019, Smith 2020).

Most countries in the world have ratified the Paris Climate Accord. Article 2 of the Accord defines the primary goals of the agreement as "holding the increase in global average temperature to well below 2 ˚C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 ˚C above pre-industrial levels." In pursuit of those goals, Article 4 commits the parties to rapidly reduce global greenhouse gas emissions "so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of the century."

Pursuant to the agreement, major emitting countries have set individual goals for reductions. At present the world is not on track to meet the goals of the Paris Accord. Despite rapid growth in the installed capacity of wind and solar energy, the percentage of global energy use derived from fossil fuels has remained nearly constant over the past decade, while global energy consumption and greenhouse gas emissions have continued to increase (EIA 2021, GCP 2021). As clean energy technologies become cost competitive, energy-related emissions can be expected to decline, but there is a substantial risk that the energy transition will not proceed rapidly enough to limit global warming to less than 2 ˚C.

Most published studies of mitigation pathways consistent with the goals of the Paris Accord envision the need to supplement clean energy development with carbon removal from natural processes and technologies such as BECCS and direct air capture (DAC) (Clarke et al., 2014). Indeed, the Intergovernmental Panel on Climate Change's modeling confirms the need to remove significant amounts of CO2 from the atmosphere and ultimately achieve net negative greenhouse gas emissions (see Figure 2).

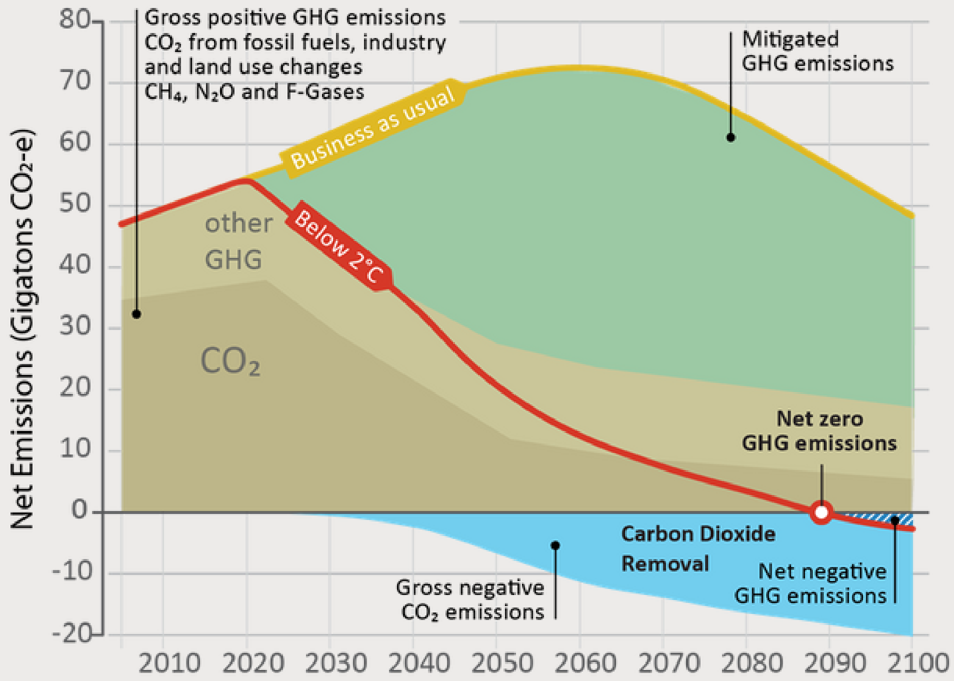


**Figure 2.** Scenarios of net greenhouse gas emissions from fossil fuels, industry and land-use changes, and CO2 removal strategies. Source: Negative Emissions Technologies and Reliable Sequestration, NASEM, 2019

# 3 /Carbon Dioxide ($CO_2$) Removal for Climate Change Mitigation

Because cutting greenhouse gas emissions across the economy will take time, carbon dioxide ($CO_2$) removal can play an important role in achieving Virginia's net-zero goals as well as those expressed by other states, countries, and institutions. They are needed both to offset emissions that are too expensive or otherwise difficult to cut and to stabilize $CO_2$ levels in the atmosphere at an acceptable level for the long term.

## Carbon Dioxide ($CO_2$) Removal (Negative Emissions)

The process of $CO_2$ removal involves two steps – taking $CO_2$ out of the atmosphere and then sequestering it so that it remains unavailable to the atmosphere for the foreseeable future, preferably permanently. This can be done through natural or technological processes. Despite their importance, there are major gaps in our understanding of $CO_2$ removal strategies, particularly in how to implement them on a broad scale.

The strategies that could be deployed in Virginia include the following:

- Reforestation and other tree planting in order to remove and sequester carbon through the growth of trees and addition of carbon to soils.
- Changes in agricultural practices which can increase long-term storage of carbon in soils and reduce greenhouse gas emissions from soils and livestock.
- Restoration of coastal ecosystems, which sequester carbon through the growth of seagrasses and expansion of tidal wetlands.
- Bioenergy with carbon capture and storage (BECCS), whereby biofuel growth removes $CO_2$ from the atmosphere which is captured when the fuels are burned for energy and stored underground.
- Direct air capture (DAC) and sequestration through technologies that pull $CO_2$ out of the atmosphere for storage in the ground.

Natural uptake of $CO_2$ already offsets emissions of greenhouse gases. From 2010 through 2019, approximately half of the $CO_2$ released into the atmosphere globally from anthropogenic sources was removed by terrestrial ecosystems and the oceans (Friedlingstein et al., 2020). As noted above, forests and other land uses in Virginia currently sequester approximately 35 percent of greenhouse gas emissions in the state.

Additional $CO_2$ removal will need to play several roles in climate mitigation in Virginia and globally. First, through regulated carbon offset markets (often referred to as cap-and-trade programs), $CO_2$ removal can lower at least the short-term cost of climate mitigation. Carbon markets that are part of a mandatory emissions reduction program allow regulated greenhouse gas emitters to assess whether to cut their own emissions or to seek more cost-effective means of mitigating those emissions by paying for emissions reductions or $CO_2$ removal elsewhere. Carbon removal projects are one of the potential sources of greenhouse gas offsets.

Second, $CO_2$ removal projects allow carbon emitters that are not yet regulated to reduce their carbon footprint voluntarily. Individuals can purchase voluntary carbon offsets and corporations can do the same or directly sponsor their own large offset projects. $CO_2$ removal strategies play a prominent role in these efforts.

Third, as more sources of greenhouse gases become regulated, some emissions will invariably prove technologically difficult or particularly expensive to eliminate. Air travel is one source that may fall into this category of recalcitrant emissions. $CO_2$ removal strategies may be needed for many years in the future to offset emissions from these sources if we are to achieve net-zero emissions.

Finally, due to the amount of $CO_2$ already in the atmosphere and that will be emitted along the path to net-zero, most published studies envision the need for significant removal of $CO_2$ from the atmosphere to ultimately achieve net negative greenhouse gas emissions by the second half of this century (see Figure 2).

## Carbon Dioxide ($CO_2$) Removal (Negative Emissions)

The Virginia Clean Economy Act requirement to develop a plan for achieving net-zero emissions from all sectors of the economy by 2045 implies some level of additional $CO_2$ removal to offset emissions from sectors such as transportation and industries which are expensive and politically difficult to cut. The balance of emissions reduction and $CO_2$ removal will ultimately depend on the costs of different technologies and practices, and those costs are likely to change rapidly in coming years.

To assess the $CO_2$ removal needs to meet Virginia's economy-wide carbon neutrality goal in 2050, we used the same integrated modeling tool used by the Intergovernmental Panel on Climate Change and the federal government to develop its national-scale decarbonization plans. The model, called the Global Change Analysis Model for the USA (GCAM-USA) allowed us to analyze the most cost-effective $CO_2$ removal strategies to meet Virginia's carbon neutrality goal by 2050.

The model includes a portfolio of technically feasible $CO_2$ removal strategies within Virginia along with the deployment of other cost-competitive $CO_2$ reduction technologies such as use of renewables to displace carbon-based sources of electricity generation. The model includes assumptions related to the cost of mitigation, applicable policies, and the rate of electrification of the transportation sector. We included the zero-carbon electricity generation mandate of the Virginia Clean Economy Act and assumed an overall goal of net-zero with no other mandates for sources other than electricity. Given current policies, that cannot be expected to entirely eliminate transportation emissions by 2050, the model results show that Virginia could need approximately 40 million tons of additional incremental $CO_2$ removal per year in 2050.

The model predicts less than ten percent of Virginia's incremental $CO_2$ removal will come from land use changes such as tree planting and agricultural practices, largely due to competing land uses. Independent estimates of the potential of nature-based $CO_2$ removal through forest restoration, changes in agricultural practices, and restoration of seagrasses and coastal wetlands confirm this relatively modest role for natural $CO_2$ removal. This highlights the need for substantial $CO_2$ removal from technological solutions to meet Virginia's 2050 net-zero carbon emissions goal.

# 4 / Strategies for Carbon Dioxide (CO2) Removal in Virginia

## Bioenergy with carbon capture and storage (BECCS)

Bioenergy with carbon capture and storage (BECCS) is a combination of two technologies that, taken together, have great potential for carbon dioxide ($CO_2$) removal. The BECCS process captures atmospheric $CO_2$ through the growth of biomass which can then be harvested and processed for bioenergy. To achieve negative emissions, the bioenergy conversion process uses technology to capture $CO_2$ released during combustion or other processing of the biomass. The captured $CO_2$ is then stored in a secure geologic repository where it can remain indefinitely. Many different forms of BECCS have been proposed. Biomass feedstocks could be corn, switchgrass, forest residues, or even municipal solid waste. Conversion processes include direct combustion to make electricity and gasification of the biomass to make synthetic liquid fuels. Existing BECCS technologies can convert biomass to synthetic liquid fuels and consume those fuels for energy, all with a negative carbon footprint.

For a region to be a viable site for a BECCS facility, access to inexpensive biomass and geologic carbon storage sites is needed. Virginia has both. It is a highly bio-productive region, with potential to grow a variety of feedstocks. Virginia also has extensive carbon storage potential (Blondes et al., 2019). Most of the geologic reservoirs that have been characterized to date are in Western Virginia and off the coast. Even though only a few small pilot demonstration projects have been done to date, the anticipated storage capacity at these locations greatly exceeds the demand.

**Methodology**

Using the Global Change Analysis Model (GCAM), we analyzed two of the most promising configurations of BECCS: biomass-based electricity generation (BECCS electricity) and biomass-based liquid fuels (BECCS liquids), both with carbon capture and storage in geologic reservoirs. We considered two types of BECCS electricity generation technologies that are equipped with $CO_2$ capture: conventional biomass-fired technology and an integrated gasification and combined cycle.

For BECCS liquid biofuels, we evaluated first-generation biofuel production technologies that use agricultural crops as feedstocks and second-generation biofuel production technologies that use bioenergy crops, forest residues, and other solid waste. [**2**]

We include a variety of assumptions about the policy and economic environments in Virginia. These include: 1) full implementation of the Virginia Clean Economy Act, but no regulation of $CO_2$ emissions from agriculture; 2) model assumptions about the relative costs of BECCS and other $CO_2$ removal strategies and emissions reduction pathways; and 3) assumptions about how the regulatory environment and available technologies and their costs would produce various combinations of emissions reductions and $CO_2$ removal strategies. One policy uncertainty is whether the Virginia Clean Economy Act would treat electricity generation from BECCS as carbon-free. The available BECCS processes do emit some $CO_2$, but they achieve net carbon-negative emissions by removing more $CO_2$ from the atmosphere than they emit.

We assumed that these processes would qualify under the Virginia Clean Economy Act as carbon-free. A different interpretation of the statute might make BECCS unavailable in Virginia as a source of electricity generation.

**Estimate of $CO_2$ removal potential**

We estimated that achieving net-zero $CO_2$ emissions in Virginia by 2050 could require more than 40 million tons of $CO_2$ per year of additional $CO_2$ removal as well as significant emissions reductions (Table 1). A key driver of potential need for incremental negative emissions is the extent to which transportation can be decarbonized by 2050 – the more cars and trucks that switch to electricity or other green fuels the less carbon removal the state will need to achieve net-zero. Our base case analysis assumes the need to offset substantial remaining carbon emissions from the transportation sector in 2050, but if decarbonization of this sector proceeds more rapidly, a lower level of offsetting negative emissions would be required.

[**2**] Liquid biofuels (even if used for transportation where end use CCS is not currently cost-effective) can still provide negative emissions if bioenergy is used to power the conversion of the biomass to a liquid fuel and $CO_2$ from the conversion process is captured and sequestered.

The GCAM model indicates that more than half of the total $CO_2$ removal in 2050 would come from BECCS electricity and about one third of the total would come from BECCS liquids. Nature-based negative emissions are projected to provide 7% of the total negative emissions in 2050 (Figure 1). These results should be viewed as indicative of potential pathways to a net-zero energy system in Virginia that relies on currently available technologies. Emerging technologies, such as green hydrogen and direct air capture (DAC), could play a greater role if some of the more optimistic cost-reduction forecasts for these technologies prove to be accurate.

The Virginia Clean Economy Act mandates use of wind, solar, and other zero-carbon electric generation technologies to eliminate emissions from the power sector.

Our modeling results indicate that electric generation using BECCS could be a comparatively low-cost means of offsetting remaining emissions from other energy uses that will be difficult to fully transition from carbon-based fuels by 2050. [**3**]

To assess the accuracy of GCAM's output for Virginia and obtain a more ground-up estimate of the capacity of natural processes for negative emissions, we determined independently the $CO_2$ removal potential for forest restoration, changes in agricultural practices, and restoration of coastal ecosystems. These estimates indicate that there is more capability to sequester $CO_2$ through natural processes in Virginia than modeled by the GCAM – approximately 20 percent of the total negative emissions needed for Virginia to meet net-zero. Those results are discussed more fully in the next three sections below.

[**3**] The role of BECCS electricity in a net-zero Virginia energy system would depend crucially on whether and how emission offsets for BECCS would be accounted for and compensated under the Virginia Clean Economy Act (VCEA) and any future legislation. Although the VCEA permits the state's investor-owned utilities to use unspecified zero-carbon electric generating technologies as well as specific targets for wind and solar, to meet the VCEA's mandates, it is not clear whether BECCS would be considered a zero-carbon source of electric generation as currently defined in the VCEA. This ambiguity is worth addressing in future legislation since BECCS generating facilities in addition to providing negative emissions also would provide a source of dispatchable power to the grid which will be of increasing value as the VCEA is implemented and the proportion of generation derived from intermittent renewables increases.

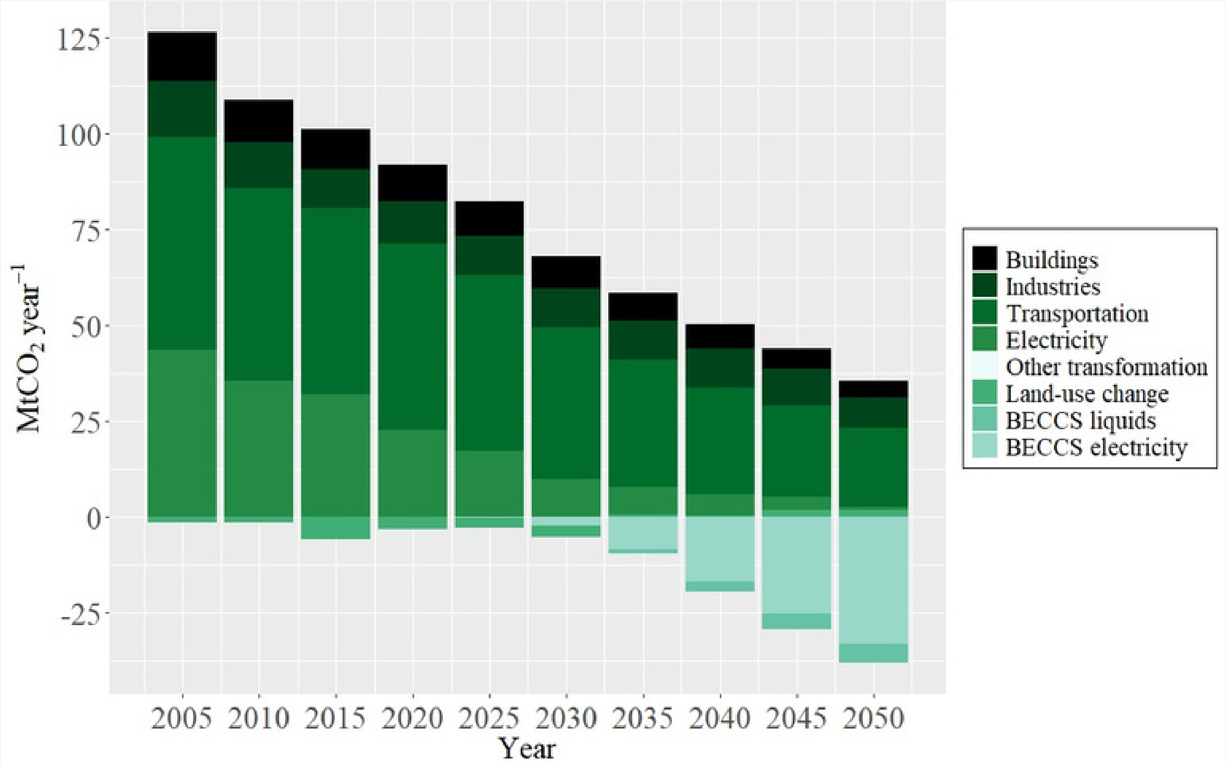


**Figure 3:** Sectoral CO2 emissions and negative emissions technologies under Virginia's carbon neutrality goal in 2050.

## Forest Restoration

When trees grow, they pull CO2 out of the atmosphere and store the carbon as biomass, primarily wood, but also as leaves and roots. In a forest, some of this carbon is periodically released, for example when leaves fall to the ground and decompose or when the forest burns in a fire. However, forests are capable of storing large amounts of carbon for extended periods of time, both in the form of tree biomass and carbon that gets integrated into forest soils (Trumbore, 2000). Through deforestation globally, humans have caused the release of approximately 770 billion tons of CO2 into the atmosphere since 1750 (Friedlingstein et al., 2020). By maintaining and expanding forests, we can remove CO2 from the atmosphere and sequester it for decades assuming proper management. Virginia's existing forests are already doing this quite well – current estimates are that 13-15 million acres of forests and urban trees in Virginia sequester 51 million tons of carbon per year.

Virginia has significant potential for reforestation and other tree planting designed to capture and sequester additional $CO_2$. Much of the state was forested before European settlement, and forests could be replanted on open and available land with a good chance of success. Using readily available modeling tools, we have calculated that there are 1.9 million acres of land highly appropriate for these strategies in Virginia that could sequester an average of 5.9 million additional tons of carbon per year through 2050.

**Methodology**

We used a dataset developed by The Nature Conservancy to assess the distribution of forest restoration opportunities in the contiguous United States to estimate how many acres in Virginia are suitable for forest restoration in terms of biophysical characteristics and existing land use (Cook-Patton et al., 2020). We only considered lands not currently in economically productive use as available for reforestation. For example, we excluded crop land and productive pasture land, but included less productive pasture land on challenging soils. We also considered the possibilities for expanding tree cover in urban areas. To arrive at an estimate, we needed to quantify carbon sequestration for each acre of reforested land over time.

The rate of carbon uptake by forests varies based on local climate, soil conditions, and forest age. To account for this, we used a spatially explicit model developed by The Nature Conservancy based on data from the United States Forest Service (see Cook-Patton et al., 2020).

**Estimate of $CO_2$ removal potential**

In addition to the 51 million tons of $CO_2$ per year currently being sequestered by Virginia forests, we estimate that new forests in Virginia could sequester a theoretical maximum of 15 million additional tons of $CO_2$ per year, declining by about 8% from 2030 to 2050 as the forests age. This mitigation could be achieved by restoring tree cover to 4.4 million acres of land that was historically forested. It includes three categories of land currently used for agriculture: pasture on challenging soils, pasture on higher quality soils, and a very small amount of cropland on challenging soils. Converting the entire 4.4 million acres to forest is not a realistic scenario. This total represents about 80% of all farmland (crops and pastures) in Virginia and 20% of all non-federal land in the state. Virginia needs to keep producing food, there are no policy proposals on the table to convert this much land to climate mitigation uses, and owners of this extent of land are not likely to convert it to forest.

To arrive at a more realistic upper bound on $CO_2$ removal from reforestation, we limited agricultural lands available for reforestation to pastures with challenging (less fertile) soils (approximately 939,000 acres) and some croplands on challenging soils in addition to open urban lands, unstocked forest patches, flood plains and streamside buffers, and other lands. This results in an estimate of 5.9 million tons of $CO_2$ per year in 2050 from reforestation on 1.9 million acres of land.

About half of the carbon sequestration potential is attributable to less productive pastures (see Table 2). The second largest opportunity, providing just over a third of the sequestration potential, is in urban open spaces. Conversion of a variety of other current land uses accounts for the rest. Reforestation potential exists across the Commonwealth (see Figure 4).


**Figure 4**. Spatial distribution of restoration of forest cover opportunities in Virginia.

The level of actual reforestation over the next thirty years will depend on a variety of factors and the decisions of thousands of landowners and communities around the state. Some of the land identified in Table 2 as having high potential for reforestation will likely be committed to other uses, such as residential or commercial development or production of solar energy rather than forest planting.

Some landowners will simply not want to convert their land to forest. The price paid to landowners to sequester carbon is likely to be a key factor in determining what level of additional CO2 removal the state actually achieves through reforestation. The 5.9 million tons per year amount represents a reasonable estimate of the maximum that might be achievable for purposes of planning and policy formulation.

| | Mitigation Potential ($tCO_2$ $yr^{-1}$) | | | Potential Area (*acres*) | Average Mitigation Density (2050) ($tCO_2$ $yr^{-1}$ $acre^{-1}$) |
|---|---|---|---|---|---|
| | *2030* | *2040* | *2050* | | |
| **Opportunity Type** | | | | | |
| Pastures | 3,094,975 | 2,973,277 | 2,886,477 | 939,435 | 3.07 |
| Urban Open Space | 2,266,100 | 2,154,420 | 2,081,315 | 668,383 | 3.11 |
| Biodiversity Climate Corridors | 569,805 | 544,385 | 527,872 | 171,433 | 3.08 |
| Frequently Flooded Areas (Floodplains) | 473,616 | 455,445 | 442,834 | 148,324 | 2.99 |
| Protected Areas | 418,261 | 401,935 | 389,601 | 126,582 | 3.08 |
| Non-Stocked Forest | 261,161 | 258,322 | 256,444 | 89,548 | 2.86 |
| Streamside Buffers (30-m) | 248,747 | 239,569 | 233,141 | 77,546 | 3.01 |
| Croplands with Challenging Soils | 157,101 | 150,334 | 145,584 | 47,119 | 3.09 |
| Shrublands and Scrublands | 56,085 | 54,686 | 53,447 | 17,827 | 3.00 |
| Post-Burn Landscapes | 32,771 | 31,654 | 30,958 | 10,353 | 2.99 |
| | | | | | |
| *Total (including croplands with challenging soils)* | *6,300,161* | *6,040,721* | *5,861,538* | *1,908,688* | *3.07* |
| Total (excluding croplands with challenging soils) | 6,143,061 | 5,890,386 | 5,715,954 | 1,861,569 | 3.07 |

**Table 2**. Potential mitigation from reforestation by opportunity type in Virginia, derived from The Nature Conservancy national database.

### Co-benefits and Trade-Offs

Reforestation provides substantial public benefits in addition to carbon sequestration. Indeed, a variety of government programs already provide landowners with incentives to plant trees on their land to achieve these benefits, including most notably increased wildlife habitat and improved water quality. Areas in Virginia with high conservation value offer large carbon mitigation opportunities. Biodiversity climate corridors identified by The Nature Conservancy could potentially sequester 0.5 million tons of $CO_2$ per year, equivalent to 9% of the statewide realistic mitigation potential, on 171,000 acres (Table 1). Almost 70% of the biodiversity climate corridor area overlaps with pastures and another 10% with urban areas. An additional 0.4 million tons of $CO_2$ per year could potentially be sequestered on 127,000 acres of protected areas. Over 80% of those acres are in pasture and another 10% are in urban areas. An additional 0.4 million tons of $CO_2$ per year could potentially be sequestered on 127,000 acres of protected areas. These data suggest that achieving significant reforestation of pastures and urban open space will enhance existing conservation goals. Conversely, achieving complete reforestation of biodiversity climate corridors and protected areas would achieve about 30% of the estimated total sequestration potential from reforestation of pastures on challenging soils. Focusing on land already identified as having high conservation value provides an effective and high value basis for prioritizing land for reforestation.

Reforestation also provides a variety of water management benefits. First, it can serve as a means of flood hazard mitigation (Ellison et al., 2017). Flood prone areas that could be reforested could sequester about 0.4 million tons of $CO_2$ per year (8% of the statewide total). Almost 70% of these areas occur in pastures and another 12% occur in urban areas. Flood mitigation provides an additional basis for prioritizing land for reforestation. The potential water quality benefits of reforestation are also significant (Neary et al., 2009). The federal government, Virginia, and other Chesapeake Bay states are currently engaged in a program to restore both local and Chesapeake Bay water quality.

As part of this effort, state and federal programs are offering landowners incentives to create and maintain streamside forested buffers. There is also substantial overlap between land targeted for streamside buffers and flood prone areas. Using conservation, flood prevention, and water quality metrics to prioritize land for reforestation provides a way to maximize climate benefits while minimizing land use tradeoffs.

Forest restoration provides an additional ecosystem service to the localities that embrace it: heat mitigation. Through physical processes that go well beyond the uptake of $CO_2$, forests provide local cooling of several degrees during the hottest times of the year (Ellison et al., 2017, Li et al., 2015). Forested landscapes moderate extreme heat, reducing extreme temperatures that put people, livestock, and crops at risk. Forests, both urban and rural, will be an essential tool for adaptation to ongoing climate change in Virginia.

The primary limiting factor for $CO_2$ sequestration through reforestation at scale is that it requires large amounts of land. Our estimate is that almost 1.9 million acres are needed. In addition, to sequester $CO_2$ in a way that effectively mitigates climate change, reforested land will have to be preserved for the long term.

Preservation of large amounts of land as forest in specific counties means that this land cannot be used for other purposes for the foreseeable future.

Restoring and protecting large amounts of forest could interfere with local goals for economic growth and development, either broadly speaking or in terms of specific projects that might conflict with reforestation. Reforestation will also take land out of potential use for solar, which also requires large amounts of land relative to fossil fuel power generation facilities. Extensive land preservation could also lower a counties real estate tax base, depending on the value of alternative realistic land uses.

The decision to restore forest on specific parcels of land around the state will be made by the owners of those parcels. How much land is reforested will depend in part on economic incentives, including how much carbon offset markets and government incentive programs pay compared to other uses of land. More analysis needs to be done to assess whether the state needs policies to focus forest restoration in ways that maximize co-benefits and minimize economic disadvantages to specific communities.

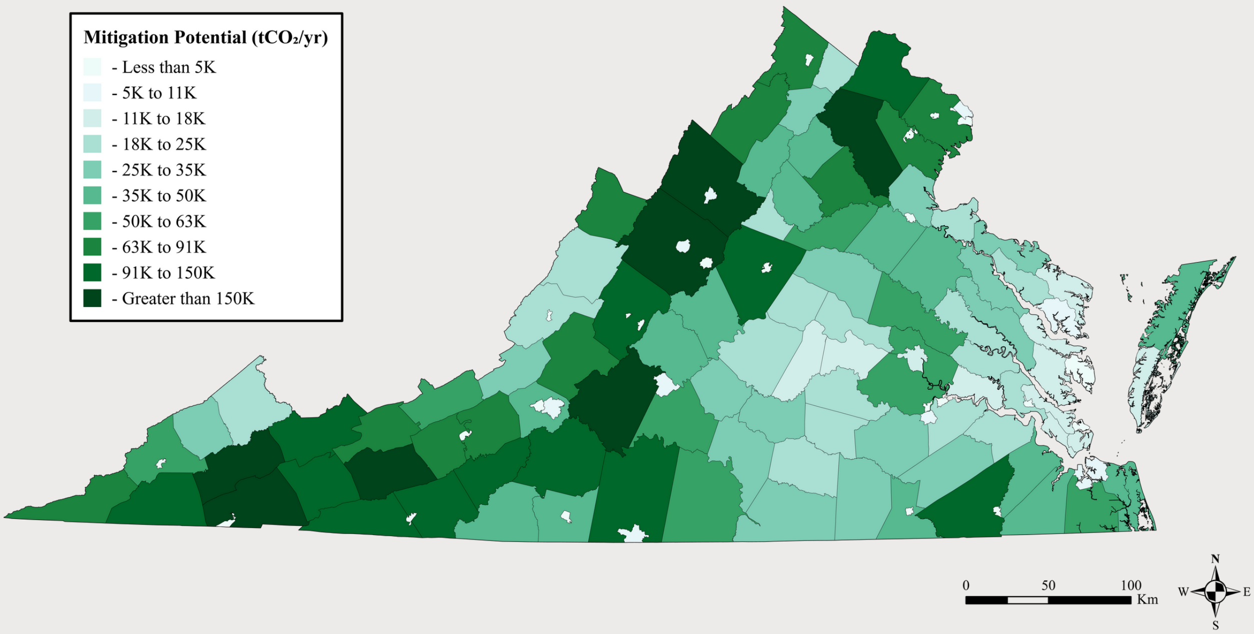


**Figure 5**. County-level sequestration potential based on restoration of forest cover opportunities in Virginia.

In addition, there are uncertainties regarding carbon sequestration through reforestation that will require further research and policy development. Although the processes by which different types of forests take up and sequester CO2 are well understood and quantified, the rate of CO2 uptake is highly dependent on local conditions (Hwang et al., 2011, Fotis et al., 2018, Yue et al., 2020). The annual rate can vary with weather and climate at a specific site, and the actual rate may not conform to the predicted average. The most accurate way of accounting for the actual rate of sequestration of a particular project is to do assessment and monitoring of each site, which may become expensive on a broad scale. These issues are not unique to Virginia and are being addressed in international climate agreements and existing carbon offset programs. Finally, carbon stored in forests can be released through unanticipated, stochastic events, most notably fire and disease (Hicke et al., 2012, McDowell et al., 2020). Any system for crediting carbon sequestered by forests will have to take into account the risk and impact of such events.

The policy challenge is to both understand the amount of carbon being sequestered and to make sure that this amount matches the amount paid for through any offset market or government incentive program. Existing offset markets have implemented tools to deal with these uncertainties (such as in California), but they need to be evaluated and updated as knowledge improves.

## Agricultural Practices

Agriculture is a major source of greenhouse gas emissions. In addition to burning fossil fuels, agriculture emits two other important greenhouse gases: methane (primarily from livestock) and $N_2O$ (primarily from fertilizer). Agriculture also can release carbon that had been stored in soils over millennia (Sanderman et al., 2017). Changes in agricultural practices can mitigate climate change in at least three ways: reducing emissions, sequestering carbon in soils, and sequestering $CO_2$ by switching some land to alternative vegetation, including trees. We estimate that, in 2050, Virginia can remove or otherwise mitigate 2.4 million tons of $CO_2$-equivalent per year on agricultural lands solely through changed management practices without taking any land out of production.

**Methodology**

To estimate carbon mitigation potential from agricultural lands and practices we used the Carbon Reduction Potential Evaluation (CaRPE) tool from the American Farmland Trust. This tool combines emission reduction coefficients from the CarbOn Management and Evaluation Tool (COMET) Planner and acreages taken from the USDA Census of Agriculture (AgCensus). The COMET Planner provides emission reduction coefficients for various cropland and pastureland management practices. Using these data, the CaRPE Tool generates county-level greenhouse gas mitigation potentials for a given acreage based on the scale of management practice adoption. This tool combines carbon uptake and sequestration (largely in soils) with actual greenhouse gas reductions. Therefore, the numbers in this section represent overall greenhouse gas mitigation, not just mitigation from $CO_2$ removal processes.

While the CaRPE tool allows for adding woody vegetation to croplands, we have not included any tree planting or other reforestation efforts in our estimate for agricultural mitigation. Virginia has just over 5 million acres of land currently in agricultural uses (other than forestry): about 3 million in cropland and 2 million in pasture land. Reforesting agricultural land represents its highest potential for $CO_2$ sequestration, but we believe this option will likely be limited to low productivity lands. As indicated above, our estimate for reforestation on farmlands includes conversion of just over 939,000 acres of marginal pastureland to forest.

Here, we are working with the remaining 1.12 million acres of pastureland plus croplands in order to develop a scenario where no additional land is taken out of agricultural production. Our estimate is based on implementing best management practices that improve soil uptake of carbon or reduce greenhouse gas emissions from the soil. To maintain a conservative approach, we assume that best management practices would only be implemented on 80 percent of these agricultural lands.

**Estimate of $CO_2$ mitigation potential**

Implementing best management practices on agricultural lands in Virginia has the potential to sequester and otherwise mitigate approximately 2.4 million tons of $CO_2$-equivalent in greenhouse gases per year (Table 2). This figure is based on implementing several complementary practices on approximately 2.5 million acres of croplands to produce mitigation of 1.7 million tons of $CO_2$-equivalent per year over existing levels. This acreage reflects the extent to which residue and tillage management and cover crops are already being implemented in the state (generating 0.7 million tons of $CO_2$-equivalent per year in mitigation).

The 2.4 million ton total also includes an 80 percent adoption rate with respect to three complementary management practices on one million acres of more productive pastureland. Range planting, nutrient management, and prescribed grazing together can generate 0.7 million tons of $CO_2$-equivalent per year.

All of these practices in some way improve soil uptake of carbon or reduce the release of greenhouse gases (primarily $N_2O$) from soil. Statewide, individual practices could yield up to 0.8 million tons of $CO_2$-equivalent per year on croplands and up to 0.5 million tons of $CO_2$-equivalent per year in pastures (Table 2). Implementation of these practices would, of course, occur primarily in the parts of the state where agricultural production is most intense, and thus the counties with the highest agricultural production also have the highest potential for mitigation (Figure 6). Mitigation potential from active farmlands (2.4 million tons of $CO_2$-equivalent per year) is less than half that of reforestation (5.9 million tons of $CO_2$-equivalent per year); yet farm-based efforts require 3.4 million acres of land and a realistic reforestation scenario requires only 1.9 million acres.

| | Emission reductions ($tCO2e\ yr^{-1}$) | ($acres$) | Mitigation Density ($tCO2e\ yr^{-1}\ acre^{-1}$) |
|---|---|---|---|
| **Agricultural practices on high quality pastureland** | total available--> | 1,193,848 | |
| Range Planting | 480,646 | 956,612 | 0.50 |
| Nutrient Management | 145,348 | 956,612 | 0.15 |
| Prescribed Grazing | 49,345 | 956,612 | 0.05 |
| *Theoretical combined pasture management* | 675,339 | 956,612 | 0.71 |
| | | | |
| **Agricultural practices on cropland** | total available--> | 3,084,003 | |
| Mulching | 797,113 | 2,467,252 | 0.32 |
| Stripcropping | 589,344 | 2,467,252 | 0.24 |
| Conservation Crop Rotation | 549,388 | 2,467,252 | 0.22 |
| Residue and Tillage Management (RTM) | 267,771 | 637,340 | 0.42 |
| Cover Crop (CC) | 602,538 | 1,127,586 | 0.53 |
| Nutrient Management (NM) | 442,304 | 2,467,252 | 0.18 |
| Combustion System Improvement (CSI) | 29,967 | 2,467,252 | 0.01 |
| *Theoretical combined cropland management* | 1,712,149 | 2,467,252 | 0.69 |
| *(RTM, CC, NM, CSI)* | | | |
| | | | |
| *Theoretical combined conservation practices* | 2,387,488 | 3,423,864 | 0.70 |

**Table 3**. Statewide mitigation potential from best management practices on agricultural lands (croplands and pastures on fertile soils). Derived from the CaRPE tool of the American Farmland Trust.

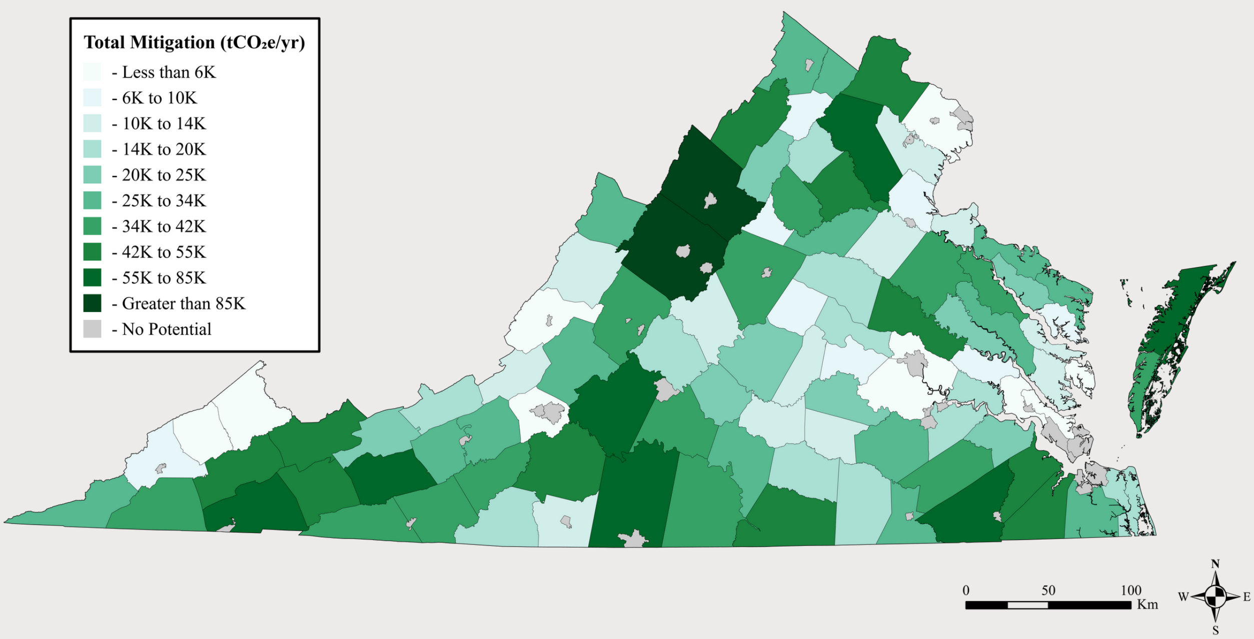


**Figure 6**. County-level mitigation potential based on agricultural practices on croplands and pasturelands (80% adoption rate).

**Co-benefits and constraints**

Many of the agricultural practices identified for carbon mitigation are already promoted by government incentive programs because of their other benefits, including improved soil health and water quality. Some practices may reduce costs for farmers because they require less fertilizer and other inputs. In addition, by improving soil health, some practices can improve the long-term productivity of land.

Implementation of carbon mitigation practices in agriculture on a large scale is a major challenge and would require large numbers of farmers to change their practices. Long-standing state and federal policies have for decades encouraged farmers to engage in similar changes to accomplish a variety of objectives, including soil conservation and improved water quality.

These policies have succeeded in many places, but the success has not been uniform. For example, efforts in Virginia and the rest of the Chesapeake Bay region to incentivize farmers to employ practices that reduce nutrient pollution have made progress but have generally fallen short of goals.

Based on this history, it is unreasonable to expect that incentive policies and offset markets will induce farmers in Virginia to deploy carbon mitigation practices on all available acres.

There are a variety of other challenges to effectively deploying carbon mitigation on agricultural lands, many of which parallel concerns related to reforestation. These include finding the right combination of modeling, site assessment, and monitoring to confirm the amount of carbon actually sequestered, as well as uncertainties about the permanence of both the practices themselves on the ground as well as the sequestration of carbon in soils. If agricultural mitigation is to be included in any carbon offset market or if carbon mitigated through these practices is to be accurately tracked, we will need additional research and policy development to design an optimal accounting procedure.

## Coastal Carbon Sequestration

In Virginia, two types of coastal ecosystems provide opportunities for carbon sequestration - subtidal seagrasses and intertidal marshes. Both types of habitats sequester carbon in plant and root biomass and in soils. The plants slow water currents and cause carbon-rich particles floating in the water to be deposited on the soils. The soils of these coastal habitats build up over time and are anoxic, slowing decomposition and locking the stored carbon in place. The Virginia portion of the Chesapeake Bay and the coastal lagoons of Virginia's Eastern Shore both have potential for restoration and for marsh migration in response to sea-level rise. We estimate that these ecosystems could capture and sequester a maximum of about 177,000 tons of additional carbon in 2050. This estimate is highly uncertain because a variety of potential factors could jeopardize restoration of these systems and reduce carbon sequestration, including accelerating sea-level rise, marine heatwaves, coastal development, and poor water quality (Katwijk et al., 2015). These factors will need to be evaluated further to best estimate potential for coastal carbon sequestration in the state.

## Seagrass

Historically, seagrass grew in abundance in the Chesapeake Bay and the shallow lagoons of Virginia's Eastern Shore. Eelgrass (Zostera marina) makes up the majority of submerged aquatic vegetation in the Chesapeake Bay and is the only seagrass species in Virginia's coastal lagoons. The amount of seagrass in Virginia waters is much diminished from historical levels due to a variety of causes including disease, poor water quality, and coastal development (Lefcheck et al., 2018). Restoration of seagrass by seeding started in the Chesapeake Bay in the 1990s. In 2001, a similar seed-based restoration effort started in Virginia's coastal lagoons (Orth and McGlathery, 2012). In April 2020, Virginia passed legislation allowing for the restoration of underwater grasses to count for carbon offset credits (Oreska et al., 2020). Seagrass restoration in Virginia has the potential to sequester an additional 46,000 tons of CO2-equivalents per year.

## Methodology

The Intergovernmental Panel on Climate Change has used a carbon sequestration potential for seagrass of 0.174 ton $CO_2$-equivalent per acre per year. Comprehensive research in the Virginia coastal lagoons yielded an almost identical rate of 0.170 ton $CO_2$-equivalent per acre per year, accounting for enhanced $CH_4$ and $N_2O$ emissions in seagrass meadows (Oreska et al., 2020). These calculations consider the enhanced sediment organic carbon and the long-term average organic carbon sequestered in biomass minus any enhanced greenhouse gas production ($CH_4$, $N_2O$, and $CO_2$).

We estimated additional sequestration through restoration on top of the amount being sequestered by existing seagrass meadows. The Virginia Institute of Marine Science (VIMS) has data on current seagrass area in the Chesapeake Bay and the Virginia coastal lagoons, which we subtracted from the total potential restoration area in both systems to calculate possible sequestration from new seagrasses (VIMS, 2019). As of 2019, the total area of seagrass in Virginia is 26,771 acres and it sequesters 4,550 tons of $CO_2$-equivalent per year.

| | Decreased Water Quality (0.5- 1.5m) | Current Water Quality (0.5- 2m) | Improved Water Quality (0.5- 2.5m) |
|---|---|---|---|
| VA Existing Seagrass (acre) | 26,771 | 26,771 | 26,771 |
| Coastal VA Lagoon Restoration (acre) | 10,601 | 10,601 | 10,601 |
| Chesapeake Bay in VA: Area of Contour (acre) | 203,600 | 284,376 | 363,504 |
| Total New Area (acre) | 190,380 | 271,156 | 350,284 |
| **Total New Carbon Sequestration (t CO2/yr)** | **79,958** | **113,886** | **147,119** |

**Table 4.** Total new area of seagrass based on contours of the Virginia portion of the Chesapeake Bay and a study done of the Virginia coastal bays (Oreska et al., 2021).

**Estimate of total $CO_2$ removal potential**

We estimate that in Virginia restoration of seagrasses can sequester up to an additional 46,088 tons of $CO_2$ per year in 2050, 44,286 tons of $CO_2$-equivalent per year in the state's portion of the Chesapeake Bay, and 1,801 tons of $CO_2$-equivalent per year in the lagoons of Virginia's Eastern Shore.

The context for seagrass restoration in the Chesapeake Bay and in the coastal lagoons is different in at least one key respect. A key limiting factor for seagrass restoration in the Chesapeake Bay is water quality. Higher water quality (and clarity) allows grasses to grow at greater depths and increases the potential area of seagrass habitat. The amount of seagrass that can be restored in the Virginia portion of the Chesapeake Bay will depend on restoring water quality. We have based our estimate of potential seagrass restoration area for the Chesapeake Bay on the Chesapeake Bay Program's 1992 submerged aquatic vegetation restoration targets, which require ongoing improvements to water quality and clarity.

The current deepest extent of submerged aquatic vegetation in the Chesapeake Bay is 2 meters (Koch and Orth, 2003).

We mapped three different scenarios: unchanged water quality (with seagrasses at 0.5 m to 2 m contours); improved water quality (with seagrasses at 0.5 m to 2.5 m contours), and declining water quality (with seagrasses at 0.5 m to 1.5 m contours). These estimates all represent a maximum that is probably not achievable (Table 4). Seagrass will not be able to grow in all of these areas due to a variety of factors other than water quality, including bottom sediment, fetch, and physical disturbances.

Water quality in the Virginia coastal bays is high, based on decades of data from the Virginia Coast Reserve Long-Term Ecological Research project led by the University of Virginia (www.vcrlter.virginia.edu). To estimate restoration potential for the Virginia coastal lagoons we used habitat modeling by Oreska et al., 2021 of existing and potential restoration sites in the Virginia Coast Reserve. Based on this modeling, the amount of habitat available for eelgrass restoration is approximately 42.9 $km^2$.

Figure 7a shows current seagrass cover in the Virginia portion of the Chesapeake Bay and the Virginia coastal bays, compared to the maximum restoration potential, depicted in Figure 7b. Our estimate also assumes that soil accretion will keep pace with sea-level rise (Koch and Orth, 2003). If sea levels rise faster than soils build up, that process would reduce available habitat for seagrasses (Table 1).

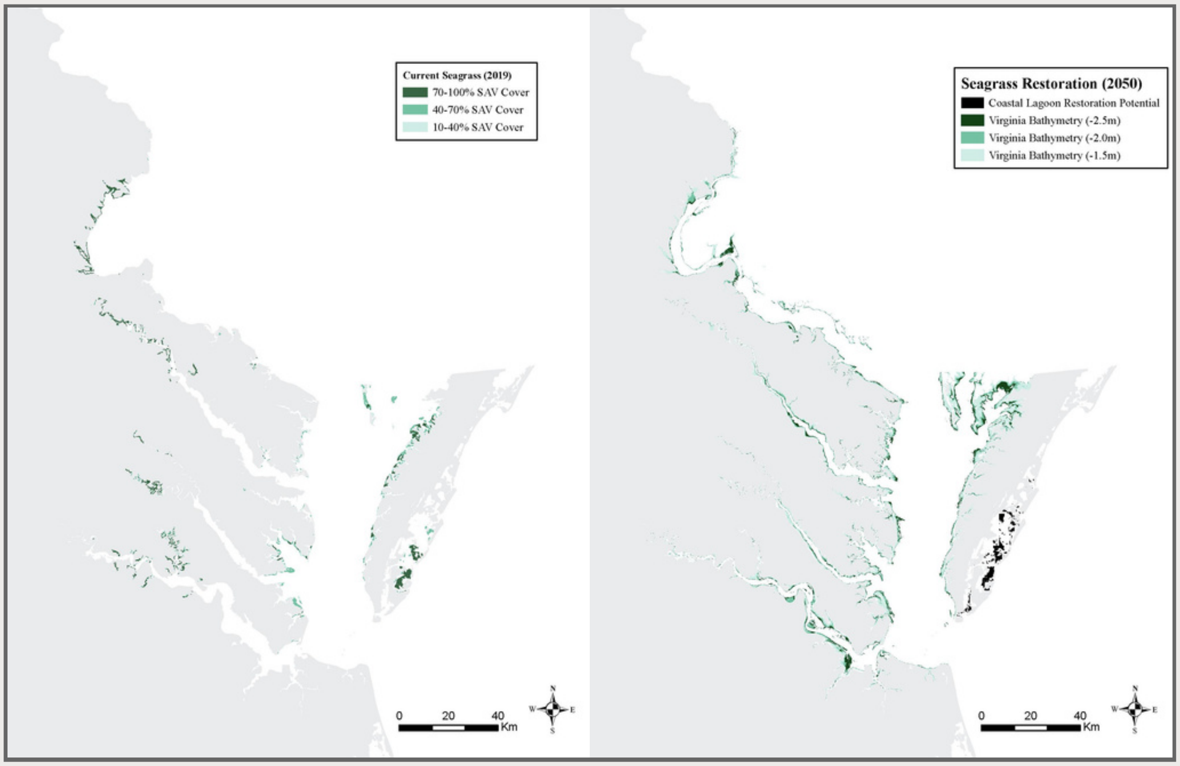


**Figure 7. a)** (left) Current seagrass cover in Virginia. **b)** (right). Maximum potential seagrass in the Virginia portion of the Chesapeake Bay and Virginia coastal bays.

## Co-benefits and constraints

Restoring seagrass offers multiple benefits to the ecosystem and economy. With increased seagrass there is a substantial decrease in turbidity levels, because seagrass reduce sediment resuspension and increase water clarity (Hansen and Reidenbach, 2012, Oreska and McGlathery, 2017). Seagrass, therefore, improve their own growing conditions by improving water clarity and increasing light levels that are key factors in the depth at which seagrass can grow.

Seagrass also acts as a buffer against shoreline erosion and plays an important role in habitat for many fish species (Aoki and McGlathery, 2018, Schaffler et al., 2013). Since seagrass is a structurally complex habitat, it supports nurseries of fish and invertebrates, such as blue crabs and scallops, early in their life cycle (Orth et al., 2020).

In the Chesapeake Bay, seagrass restoration has so far failed to achieve the goals set. This is largely influenced by water quality. Even though some increase in water quality has had a positive impact on seagrass meadows in the Chesapeake Bay, excess phosphorus and nitrogen from fertilizer, manure deposits, and urban runoff continue to affect seagrass expansion (Lefcheck et al., 2018). Climate change also threatens seagrass since temperatures above 28 ˚C have been linked to significant eelgrass die off (Sobocinski et al., 2013). Restoration of riparian areas and nutrient management throughout Virginia will significantly influence the clarity of the Chesapeake Bay and increase the depth to which seagrass can grow and the potential area for restoration.

Another possible barrier to seagrass restoration is concern that restoration may compete with the expansion of aquaculture. This is especially true for the coastal lagoons. After 1933, the disappearance of seagrass led to the collapse of the local bay scallop industry. Watermen switched to harvesting hard clams (Mercenaria mercenaria) in large numbers. Now these hard clams are cultured in clam beds within shallow areas (<1 m). This land is leased by the Commonwealth of Virginia for shellfish planting (Oreska et al., 2021). For this reason, it is unlikely that the full potential of restoration of seagrass in all suitable areas will be realized.

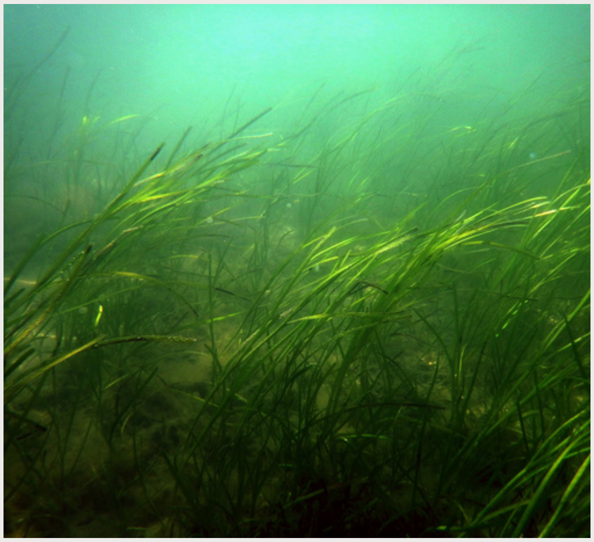

Photo by: Perter Berg

## Coastal Marshes

Coastal marshes and other intertidal wetlands are effective at sequestering carbon. Similar to seagrass meadows, the soil in marsh areas is oxygen poor which results in a very slow breakdown of plant material and long-term retention of carbon in soils. Marshes also accumulate soils and accrete vertically to keep pace with rising seas. Climate change and sea-level rise present both a risk and an opportunity for these ecosystems. Some coastal marshes may not keep pace with rising seas and may become too deeply submerged and die, releasing their stored carbon back to the atmosphere. However, with rising sea levels, marshes can also migrate inland and encroach on uplands. Managing shorelines to allow for this migration is important for maintaining the natural carbon sink of marsh ecosystems as sea levels rise. If this does not happen, there is a high risk that wetland loss from sea-level rise will exceed any gain. Storms can also cause erosion of marsh edges releasing the stored carbon in marsh peat, which may get redeposited on marsh soils, oxidized and released to the atmosphere as $CO_2$, or exported to other coastal and oceanic regions. Marsh erosion could therefore lead to accelerated marsh habitat loss along the seaward edges (Leatherman, 2000).

If managing marsh migration is made a priority, it appears that the amount of $CO_2$ sequestered by marshes could increase over time with a 1 foot increase in sea level by 2050. We estimate that with proper management of shorelines, Virginia coastal marshes can sequester an additional 131,000 tons of $CO_2$ per year by 2050.

### Methodology

First we need to assess where marshes are likely to form and to persist. Our estimates only consider estuarine and brackish transitional wetlands. Coastal elevation plays a large role in the ability for a marsh to migrate as the sea level rises. In areas with low slope, tidal marshes will expand or maintain size because of the persistence of shallow water. In areas with high slope or where the shoreline has been armored or built up, marsh loss is more likely to occur because marshes cannot migrate inland and water will simply get deeper, permanently flooding the marshland (Mitchell, 2020).

To assess total marsh area changes over time, we used the National Oceanic and Atmospheric Association (NOAA) marsh migration tool (NOAA, 2016). This tool represents the potential distribution of each wetland type based on land elevation and future inundation by sea-level rise. This includes marsh gain and loss due to flooding but does not include marsh edge erosion. The National Oceanic and Atmospheric Association data were not time sensitive, so the tool does not include marsh accretion or a sea-level rise rate, which we added using our own model. Our model used the baseline wetland data from the National Oceanic and Atmospheric Association at year 2000 and assumed a constant 5 mm accretion rate (Mitchell et al., 2020). It then assessed whether wetland accretion will keep up with sea-level rise to determine whether existing and new wetlands will persist. For this analysis, we used a sea-level rise of 1 foot by 2050. This is lower than the 2.2 foot sea-level rise (Boon et al., 2018) adopted by Governor Northam. If we had used the 2.2 foot of sea-level rise and the same 5 mm accretion rate, we estimate 78,580 acres of estuarian and brackish marshes would be lost by 2050.

To estimate the rate of $CO_2$ sequestration by marshes, we used a range of estimates: 0.58 tons of $CO_2$ per acre per year for temperate tidal marshes between 30˚ and 40˚ northern hemisphere (Wang et al., 2020), 0.89 tons of $CO_2$ per acre per year, from the International Academy of Science's report on carbon sequestration (National Academies of Sciences, Engineering, and Medicine, 2017), and 1.38 tons of $CO_2$ per acre per year, from the Maryland portion of the Chesapeake Bay (Chmura et al., 2003). Table 5 shows the potential for marsh migration and carbon sequestration for 1 foot of sea-level rise and these different sequestration rates in 2050, and Figure 8 shows the change in extent of marshes from year 2000 to 2050.

| Wetland Type | 2000 Baseline Area (acres) | 2050 Area (acres) | New Wetlands Area (acres) | New Net Carbon Sequestration Rate (0.58t C/acres/yr) | New Net Carbon Sequestration Rate (0.89t C/acres/yr) | New Net Carbon Sequestrion Rate (1.38t C/acres/yr) |
|---|---|---|---|---|---|---|
| Brackish/Transition Wetland | - | 72,849 | 72,849 | 42,253 | 64,836 | 100,532 |
| Estuarine Wetland | 192,167 | 214,629 | 22,462 | 13,028 | 19,991 | 30,998 |
| | | | | | | |
| **Total** | **192,167** | **287,478** | **95,311** | **55,281** | **84,827** | **131,530** |

**Table 5**. Marsh area and carbon sequestration in Virginia based off of 1 foot of sea-level rise in 2050.

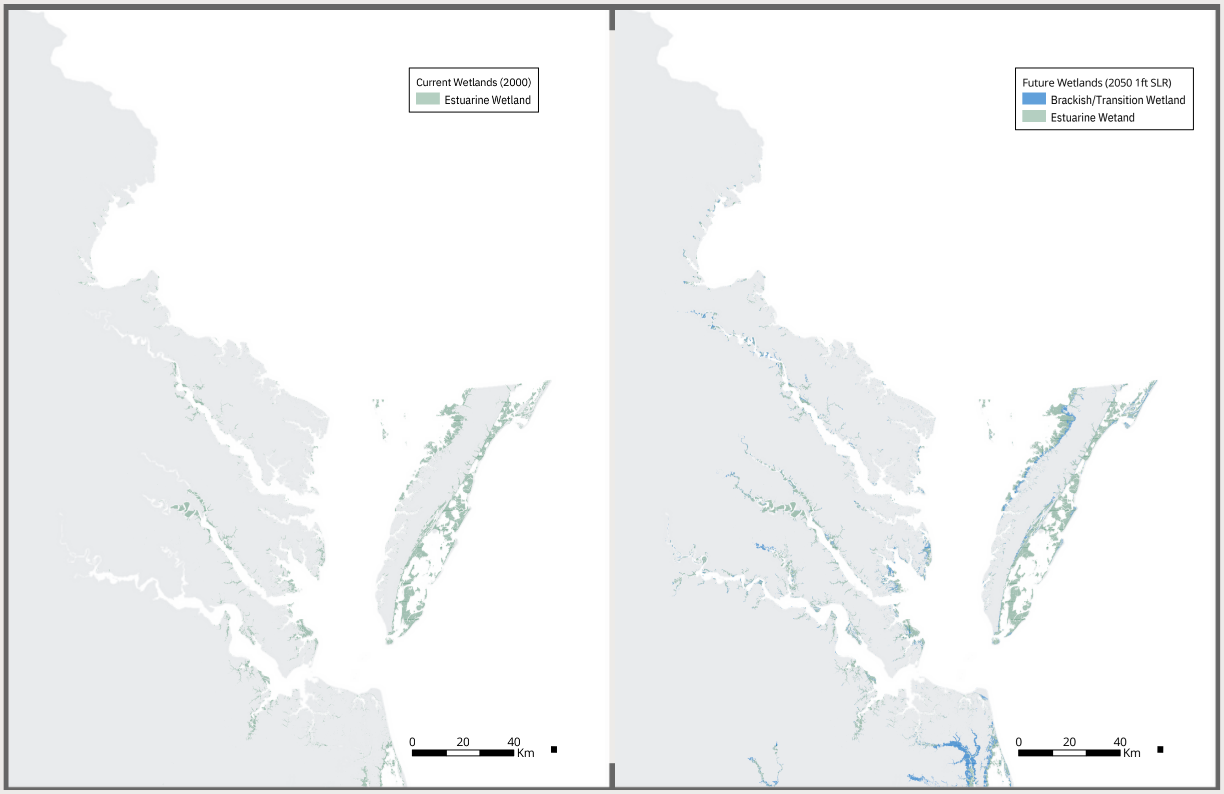


**Figure 8**. Map **a.** (left) extent of estuarine wetlands in the year 2000, and **b**. (right) extent of estuarine and brackish/transition wetlands in 2050 assuming 1 foot of sea-level rise.

### Estimate of carbon sequestration potential

Using the range of $CO_2$ sequestration rates in Table 5, we estimate that if protection of existing wetlands and creation of new ones is made a priority in Virginia, the state could sequester an additional 55,743–131,141 tons of $CO_2$-equivalent per year in coastal wetlands by 2050. The amount that Virginia marshes actually sequester will depend on a variety of factors, including the sea-level rise rate, the extent to which communities and landowners harden the coast, and efforts by governments and private landowners to protect existing wetlands and allow their migration. From our analysis, there is a significant risk that inundation of existing wetlands will produce more greenhouse gas emissions than new wetlands will sequester if the state does not focus on creating conditions appropriate for wetland migration. Active efforts to protect and allow for wetland migration will be needed to ensure that Virginia achieves a net carbon benefit as the sea level rises.

### Co-benefits and constraints

Along with sequestering carbon, coastal marshes protect coasts from storms, are essential in nutrient cycling, and provide nursery grounds that support commercial fisheries. These marshes are valued at about $24711 per acre for their ecosystem services (Kirwan and Megonigal, 2013). Marshes also protect against shoreline erosion at a lower cost than barrier construction and could be an alternative for communities to protect them from storm damage. The above ground portion of the plants dampens wave energy, and marshes promote soil accretion which increases elevation relative to sea-level rise (Moller et al., 1999). Belowground plant roots also stabilize soil and slow rates of erosion. Salt marsh dependent species of interest to humans, such as the blue crab, are greatly reduced due to salt marsh destruction (Lipcius et al., 2005).

Around 25–50 percent of the world's coastal tidal wetlands have been lost as a result of conversion into land for agriculture and aquaculture uses (Pendleton et al., 2012). As discussed earlier, conflicting land uses and social resistance will be two of the biggest barriers to further marsh creation, particularly as sea levels rise and migrating marshes might threaten existing land uses like agriculture.

Land uses, such as developed infrastructure, can impede migration directly and alter sediment delivery rates (Kirwan and Megonigal, 2013). The transition of wetlands can also be susceptible to events such as fires, insect outbreaks, and hurricanes. Biodiversity can also be affected by upland conversion, because wetland migration provides an opportunity for invasive species to take root (Kirwan and Gedan, 2019). Some models predict marsh loss in the Chesapeake Bay over the next 50- 60 years, especially with accelerated rates of sea-level rise. This is an uncertain future, and different methodologies and research lead to differing conclusions about the potential for marsh gain or loss (Mitchell et al., 2020)

Farm and forest land uses relative to other land uses such as exurban housing, roads, and solar. A total of 580 acres of permitted solar appear in this image.

# 5 /Conclusions

Maintenance and expansion of Virginia's nature-based carbon sinks and deployment of engineered carbon removal strategies can complement rapid reduction of greenhouse gas emissions within the Commonwealth. Analysis conducted for this report, as well as other recent analyses of emissions reduction pathways for Virginia, indicate that it is technically and economically feasible for the Commonwealth to achieve net-zero economy-wide energy related carbon dioxide ($CO_2$) emissions by 2050. Core strategies for achieving that goal cost-effectively include decarbonizing electric generation, as mandated by the Virginia Clean Energy Act, expanding electrification of transportation and the building sector, using zero-carbon fuels where electrification is not cost-effective, and deploying carbon removal technologies to offset any remaining emissions.

Substantial sequestration of carbon by existing land uses in Virginia already offsets 51.8 million tons of current greenhouse gas emissions in the state.

Our analysis indicates that more than 40 million tons of remaining energy related emissions in Virginia would need to be offset in 2050 if the baseline transportation sector assumptions of the Global Change Analysis Model (GCAM) prove to be accurate. Reforestation of marginal agricultural land, expansion of urban tree cover, and restoration of seagrass meadows and coastal marshes could potentially provide as much 8.6 million tons of carbon removal annually in 2050, roughly 20 percent of the needed carbon removal. If decarbonization of transportation in Virginia is not significant by 2050 substantial deployment of bioenergy with carbon capture and storage (BECCS) and/or other engineered negative emissions technologies will be required to achieve net-zero energy-related emissions.

The analysis conducted for this report also indicates that the Commonwealth can go beyond net-zero $CO_2$ emissions and seek to achieve net-negative $CO_2$ emissions by 2050.

That more ambitious goal can be realized by emphasizing economy-wide emissions reductions and implementing the strategies needed to achieve net-zero energy related emissions while safeguarding and expanding Virginia's current nature-based carbon sinks. A commitment by Virginia to achieve net-negative greenhouse gas emissions by mid-century would provide impetus for other state and national governments to increase their emissions reduction commitments and initiatives at a critical juncture in global efforts to limit global warming.

Subsequent phases of University of Virginia's Climate Restoration Initiative will explore policy and programmatic options to increase natural carbon sinks and efficiently deploy engineered negative emission technologies within the Commonwealth. Key issues that require further research and analysis include:

- Spatially detailed analyses of co-benefits of nature-based carbon removal strategies, including watershed protection, biodiversity conservation and other co-benefits of expanding reforestation, seagrass and coastal marsh restoration, and carbon-sequestering land management practices.
- Tradeoffs and optimal use of forest and agricultural land in Virginia for carbon sequestration and renewable energy generation.
- Further analysis of the costs, benefits, and production capacity of BECCS and carbon-neutral biofuels in Virginia in the context of an economy-wide decarbonization strategy.
- Potential revisions of the Virginia Clean Economy Act, the Regional Greenhouse Gas Initiative guidelines, and other legislation and regulations to promote beneficial investment in nature-based and engineered carbon-removal strategies.
- Economic incentives and other policy mechanisms for maintaining and expanding Virginia's forests, coastal wetlands, seagrass meadows, soil carbon stocks, and other natural carbon sinks.
- Equity implications of promoting natural and engineered sources of negative emissions given alternative policies and incentive structures.

Amazon. 2019. "Amazon Co-Founds the Climate Pledge, Setting Goal to Meet the Paris Agreement 10 Years Early | Amazon.com, Inc. - Press Release." https://press.aboutamazon.com/news-releases/news-release-details/amazon-co-founds-climate-pledge-setting-goal-meet-paris/.

American Farmland Trust. 2019. "Carbon Reduction Potential Evaluation." June 23, 2019. https://carpe.shinyapps.io/CarpeTool/.

Aoki, Lillian, and KJ McGlathery. 2018. "Restoration Enhances Denitrification and DNRA in Subsurface Sediments of Zostera Marina Seagrass Meadows." *Marine Ecology Progress Series* 602 (August). https://doi.org/10.3354/meps12678.

Blondes, Madalyn S., Matthew D. Merrill, Steven T. Anderson, and Christina A. DeVera. 2019. "Carbon Dioxide Mineralization Feasibility in the United States." USGS Numbered Series 2018–5079. *Carbon Dioxide Mineralization Feasibility in the United States*. Vol. 2018–5079. Scientific Investigations Report. Reston, VA: U.S. Geological Survey. https://doi.org/10.3133/sir20185079.

Boon, John, Molly Mitchell, Jon Loftis, and David Malmquist. 2018. "Anthropocene Sea Level Change: A History of Recent Trends Observed in the U.S. East, Gulf, and West Coast Regions." *Reports*, February. https://doi.org/10.21220/V5T17T.

Chmura, Gail L., Shimon C. Anisfeld, Donald R. Cahoon, and James C. Lynch. 2003. "Global Carbon Sequestration in Tidal, Saline Wetland Soils." *Global Biogeochemical Cycles* 17 (4). https://doi.org/10.1029/2002GB001917.

Clarke, Leon, et al. 2014. "Assessing Transformation Pathways." In *Climate Change 2014 Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781107415416.

Cook-Patton, Susan C., Trisha Gopalakrishna, Adam Daigneault, Sara M. Leavitt, Jim Platt, Sabrina M. Scull, Oyut Amarjargal, et al. 2020. "Lower Cost and More Feasible Options to Restore Forest Cover in the Contiguous United States for Climate Mitigation." *One Earth* 3 (6): 739–52. https://doi.org/10.1016/j.oneear.2020.11.013.

DEQ. 2021. "Virginia Greenhouse Gas Inventory – 2018." https://www.deq.virginia.gov/home/showpublisheddocument/12633/637725680592630000.

Ellison, David, Cindy E. Morris, Bruno Locatelli, Douglas Sheil, Jane Cohen, Daniel Murdiyarso, Victoria Gutierrez, et al. 2017. "Trees, Forests and Water: Cool Insights for a Hot World." *Global Environmental Change* 43 (March): 51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002.

Fotis, Alex T., Timothy H. Morin, Robert T. Fahey, Brady S. Hardiman, Gil Bohrer, and Peter S. Curtis. 2018. "Forest Structure in Space and Time: Biotic and Abiotic Determinants of Canopy Complexity and Their Effects on Net Primary Productivity." *Agricultural and Forest Meteorology* 250–251 (March): 181–91. https://doi.org/10.1016/j.agrformet.2017.12.251.

Friedlingstein, Pierre, Michael O'Sullivan, Matthew W. Jones, Robbie M. Andrew, Judith Hauck, Are Olsen, Glen P. Peters, et al. 2020a. "Global Carbon Budget 2020." *Earth System Science Data* 12 (4): 3269–3340. https://doi.org/10.5194/essd-12-3269-2020.

Gedan, Keryn, Matthew Kirwan, Erin Wolanski, Edward Barbier, and Brian Silliman. 2010. "The Present and Future Role of Coastal Wetland Vegetation in Protecting Shorelines: Answering Recent Challenges to the Paradigm," December. https://link.springer.com/article/10.1007/s10584-010-0003-7.

"Greenhouse Gases | Virginia DEQ." n.d. Accessed March 7, 2022. https://www.deq.virginia.gov/air/greenhouse-gases.

Hansen, Jennifer, and Matthew Reidenbach. 2012. "Wave and Tidally Driven Flows in Eelgrass Beds and Their Effect on Sediment Suspension." *Marine Ecology Progress Series* 448 (February): 271.

Hicke, Jeffrey A., Craig D. Allen, Ankur R. Desai, Michael C. Dietze, Ronald J. Hall, Edward H. (Ted) Hogg, Daniel M. Kashian, et al. 2012. "Effects of Biotic Disturbances on Forest Carbon Cycling in the United States and Canada." *Global Change Biology* 18 (1): 7–34. https://doi.org/10.1111/j.1365-2486.2011.02543.x.

Hwang, Taehee, Conghe Song, James M. Vose, and Lawrence E. Band. 2011. "Topography-Mediated Controls on Local Vegetation Phenology Estimated from MODIS Vegetation Index." *Landscape Ecology* 26 (4): 541–56. https://doi.org/10.1007/s10980-011-9580-8.

"International Energy Outlook - U.S. Energy Information Administration (EIA)." n.d. Accessed March 16, 2022. https://www.eia.gov/outlooks/ieo/index.php.

IPCC. 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry /The Intergovernmental Panel on Climate Change. Ed. by Jim Penman*. Edited by Jim Penman. Hayama, Kanagawa.

Katwijk, Marieke M., Anitra Thorhaug, Núria Marbà, Robert J. Orth, Carlos M. Duarte, Gary A. Kendrick, Inge H. J. Althuizen, et al. 2016. "Global Analysis of Seagrass Restoration: The Importance of Large-Scale Planting." *Journal of Applied Ecology* 53 (2): 567–78. https://doi.org/10.1111/1365-2664.12562.

Kirwan, Matthew, and Patrick Megonigal. 2013. "Tidal Wetland Stability in the Face of Human Impacts and Sea-Level Rise |." *Nature*, December. https://doi.org/10.1038/nature12856.

Koch, Evamaria, and Robert Orth. 2003. "Seagrasses of the Mid-Atlantic Coast of the USA." In , 216–23.

Leatherman, Stephen P., Keqi Zhang, and Bruce C. Douglas. 2000. "Sea Level Rise Shown to Drive Coastal Erosion." *Eos, Transactions American Geophysical Union* 81 (6): 55–57. https://doi.org/10.1029/00EO00034.

Lefcheck, Jonathan S., Robert J. Orth, William C. Dennison, David J. Wilcox, Rebecca R. Murphy, Jennifer Keisman, Cassie Gurbisz, et al. 2018. "Long-Term Nutrient Reductions Lead to the Unprecedented Recovery of a Temperate Coastal Region." *Proceedings of the National Academy of Sciences* 115 (14): 3658–62. https://doi.org/10.1073/pnas.1715798115.

Li, Yan, Maosheng Zhao, Safa Motesharrei, Qiaozhen Mu, Eugenia Kalnay, and Shuangcheng Li. 2015. “Local Cooling and Warming Effects of Forests Based on Satellite Observations.” *Nature Communications* 6 (1): 6603. https://doi.org/10.1038/ncomms7603.

Lipcius, R., R. Seitz, Michael S. Seebo, and Duamed Colón-Carrión. 2005. “Density, Abundance and Survival of the Blue Crab in Seagrass and Unstructured Salt Marsh Nurseries of Chesapeake Bay.” https://doi.org/10.1016/J.JEMBE.2004.12.034.

McDowell, Nate G., Craig D. Allen, Kristina Anderson-Teixeira, Brian H. Aukema, Ben Bond-Lamberty, Louise Chini, James S. Clark, et al. 2020. “Pervasive Shifts in Forest Dynamics in a Changing World.” *Science* 368 (6494): eaaz9463. https://doi.org/10.1126/science.aaz9463.

Mcglathery, Karen, Robert Christian, Linda Blum, Debbie Daniel, Margot Miller, James Spitler, and Overman. 2008. “Water Quality of Virginia Coastal Bays - Physical Data 1992-2008.” VCR. http://www.vcrlter.virginia.edu/cgi-bin/browseData.cgi.

“Microsoft Will Be Carbon Negative by 2030.” 2020. The Official Microsoft Blog. January 16, 2020. https://blogs.microsoft.com/blog/2020/01/16/microsoft-will-be-carbon-negative-by-2030/.

Mitchell, Molly, Julie Herman, and Carl Hershner. 2020. “Evolution of Tidal Marsh Distribution under Accelerating Sea Level Rise.” *Wetlands* 40 (6): 1789–1800. https://doi.org/10.1007/s13157-020-01387-1.

Möller, I., T. Spencer, J. R. French, D. J. Leggett, and M. Dixon. 1999. “Wave Transformation Over Salt Marshes: A Field and Numerical Modelling Study from North Norfolk, England.” *Estuarine, Coastal and Shelf Science* 49 (3): 411–26. https://doi.org/10.1006/ecss.1999.0509.

NAP. 2017. “Coastal Blue Carbon Approaches for Carbon Dioxide Removal and Reliable Sequestration.” In . https://doi.org/10.17226/24965.

National Academies of Sciences, Engineering, and Medicine. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259.

Neary, Daniel G., George G. Ice, and C. Rhett Jackson. 2009. “Linkages between Forest Soils and Water Quality and Quantity.” *Forest Ecology and Management*, Forest Soil Science: Celebrating 50 Years of Research on Properties, Processes and Management of Forest Soils Forest Soil Science: Celebrating 50 Years of Research on Properties, Processes and Management of Forest Soils Forest Soil Science: Celebrating 50 Years of Research on Properties, Processes and Management of Forest Soils Forest Soil Science: Celebrating 50 Years of Research on Properties, Processes and Management of Forest Soils, 258 (10): 2269–81. https://doi.org/10.1016/j.foreco.2009.05.027.

NOAA. 2016. “Sea Level Rise Wetland Impacts and Migration.” NOAA. https://coast.noaa.gov/digitalcoast/data/slr-wetland.html.

Ogle, Stephen M., and Werner A. Kurz. 2021. “Land-Based Emissions.” *Nature Climate Change* 11 (5): 382–83. https://doi.org/10.1038/s41558-021-01040-7.

Oreska, Matthew P. J., Karen J. McGlathery, Lillian R. Aoki, Amélie C. Berger, Peter Berg, and Lindsay Mullins. 2020. “The Greenhouse Gas Offset Potential from Seagrass Restoration.” *Scientific Reports* 10 (1): 7325. https://doi.org/10.1038/s41598-020-64094-1.

Oreska, Matthew P. J., Karen J. McGlathery, and John H. Porter. 2017. “Seagrass Blue Carbon Spatial Patterns at the Meadow-Scale.” *PLOS ONE* 12 (4): e0176630. https://doi.org/10.1371/journal.pone.0176630.

Oreska, Matthew P. J., Karen J. McGlathery, Patricia L. Wiberg, Robert J. Orth, and David J. Wilcox. 2021. “Defining the Zostera Marina (Eelgrass) Niche from Long-Term Success of Restored and Naturally Colonized Meadows: Implications for Seagrass Restoration.” *Estuaries and Coasts* 44 (2): 396–411. https://doi.org/10.1007/s12237-020-00881-3.

Orth, Robert J., Jonathan S. Lefcheck, Karen S. McGlathery, Lillian Aoki, Mark W. Luckenbach, Kenneth A. Moore, Matthew P. J. Oreska, Richard Snyder, David J. Wilcox, and Bo Lusk. 2020. “Restoration of Seagrass Habitat Leads to Rapid Recovery of Coastal Ecosystem Services.” *Science Advances* 6 (41): eabc6434. https://doi.org/10.1126/sciadv.abc6434.

Orth, Robert J., and Karen J. McGlathery. 2012. “Eelgrass Recovery in the Coastal Bays of the Virginia Coast Reserve, USA.” *Marine Ecology Progress Series* 448 (February): 173–76. https://doi.org/10.3354/meps09596.

Pendleton, Linwood, Daniel C. Donato, Brian C. Murray, Stephen Crooks, W. Aaron Jenkins, Samantha Sifleet, Christopher Craft, et al. 2012. “Estimating Global ‘Blue Carbon’ Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems.” *PLOS ONE* 7 (9): e43542. https://doi.org/10.1371/journal.pone.0043542.

Sanderman, Jonathan, Tomislav Hengl, and Gregory J. Fiske. 2017. “Soil Carbon Debt of 12,000 Years of Human Land Use.” *Proceedings of the National Academy of Sciences* 114 (36): 9575–80. https://doi.org/10.1073/pnas.1706103114.

Schaffler, Jason J., Jacques van Montfrans, Cynthia M. Jones, and Robert J. Orth. 2013. “Fish Species Distribution in Seagrass Habitats of Chesapeake Bay Are Structured by Abiotic and Biotic Factors.” *Marine and Coastal Fisheries* 5 (1): 114–24. https://doi.org/10.1080/19425120.2013.804013.

Shobe, William, Arthur Small, and Anthony Artuso. 2021. “Decarbonizing Virginia’s Economy: Pathways to 2050.” Energy Transition Initiative, University of Virginia; Evolved Energy Research. https://energytransition.coopercenter.org/reports/decarbonizing-virginia-pathways-2050.

Smith. 2020. “Microsoft Will Be Carbon Negative by 2030.” *The Official Microsoft Blog* (blog). January 16, 2020. https://blogs.microsoft.com/blog/2020/01/16/microsoft-will-be-carbon-negative-by-2030/.

Sobocinski, Kathryn L., Robert J. Orth, Mary C. Fabrizio, and Robert J. Latour. 2013. “Historical Comparison of Fish Community Structure in Lower Chesapeake Bay Seagrass Habitats.” *Estuaries and Coasts* 36 (4): 775–94. https://doi.org/10.1007/s12237-013-9586-3.

The Nature Conservancy. 2021. “State Spatial Data.” https://tnc.app.box.com/s/19vuqit0uukpde0q5xtgqkdtlng72c8j.

Trumbore, Susan. 2000. “Age of Soil Organic Matter and Soil Respiration: Radiocarbon Constraints on Belowground C Dynamics.” *Ecological Applications* 10 (2): 399–411. https://doi.org/10.1890/1051-0761(2000)010[0399:AOSOMA]2.0.CO;2.

USEPA. 2021. “Inventory of U.S. Greenhouse Gas Emission and Sinks.” EPA-430-R21-005. https://www.epa.gov/sites/default/files/2021-04/documents/us-ghg-inventory-2021-main-text.pdf?VersionId=wEy8wQuGrWS8Ef_hSLXHy1kYwKs4.ZaU.

VIMS. 2019. “SAV Reports & Data.” SAV Report. Chesapeake Bay: Virginia Institute of Marine Science. https://www.vims.edu/research/units/programs/sav/reports/2019/index.php.

Wang, Faming, Christian J Sanders, Isaac R Santos, Jianwu Tang, Mark Schuerch, Matthew L Kirwan, Robert E Kopp, et al. 2021. “Global Blue Carbon Accumulation in Tidal Wetlands Increases with Climate Change.” *National Science Review* 8 (9). https://doi.org/10.1093/nsr/nwaa296.

Yue, Qingmin, Minhui Hao, Xiaoyu Li, Chunyu Zhang, Klaus von Gadow, and Xiuhai Zhao. 2020. “Assessing Biotic and Abiotic Effects on Forest Productivity in Three Temperate Forests.” *Ecology and Evolution* 10 (14): 7887–7900. https://doi.org/10.1002/ece3.6516.

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